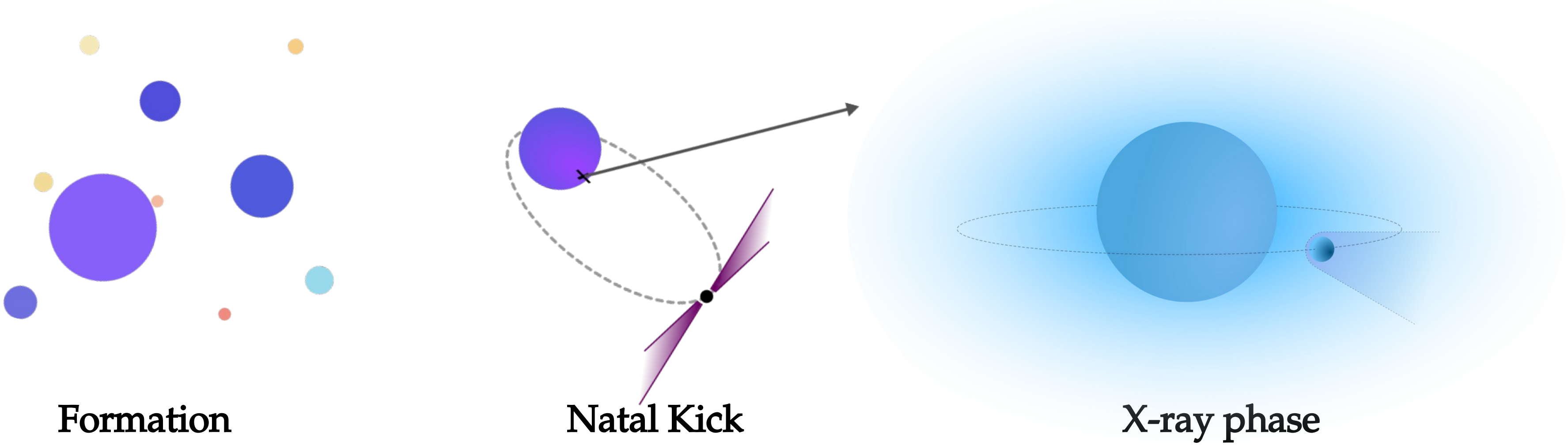
A Catalogue of X-ray binaries to understand their evolution



Francis Fortin – Postdoc LabEx UnivEarthS – APC

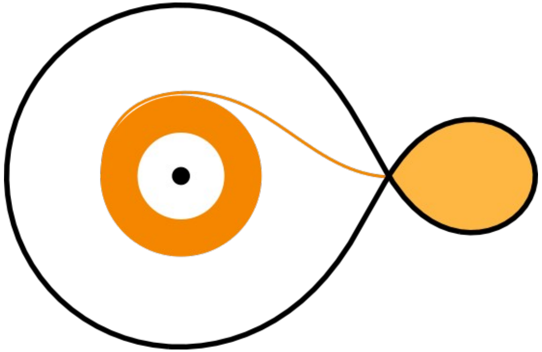
X-ray binaries cheat sheet

- Discovered in the 1960’
- Hard X-ray emission powered by accretion
- Transient or persistent
- Disks, jets, stellar winds…

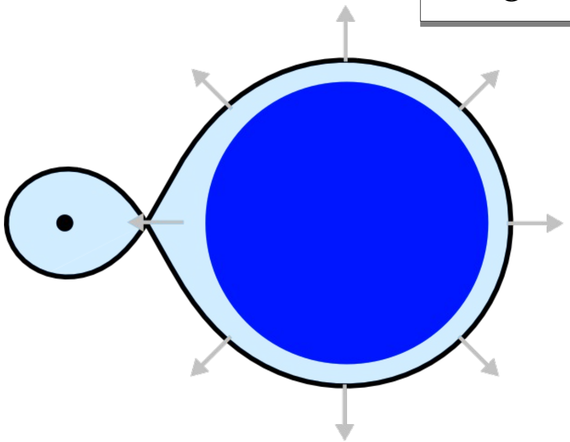
Companion star: low mass (< 1 M☉) or high mass (> 8 M☉)

Low Mass X-ray Binaries

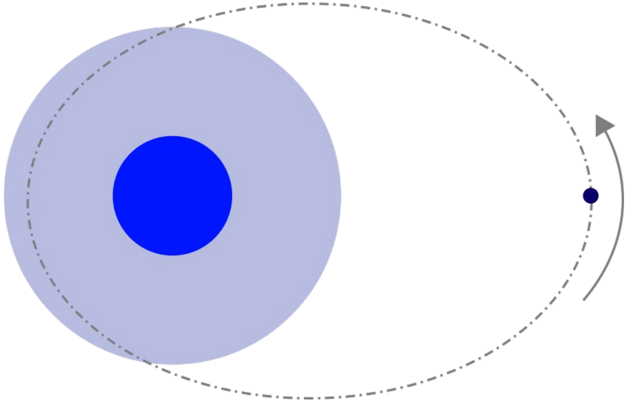
High Mass X-ray Binaries



Roche lobe overflow



Wind accretion



Decretion disk

Evolution of High-Mass X-ray Binaries (HMXBs)

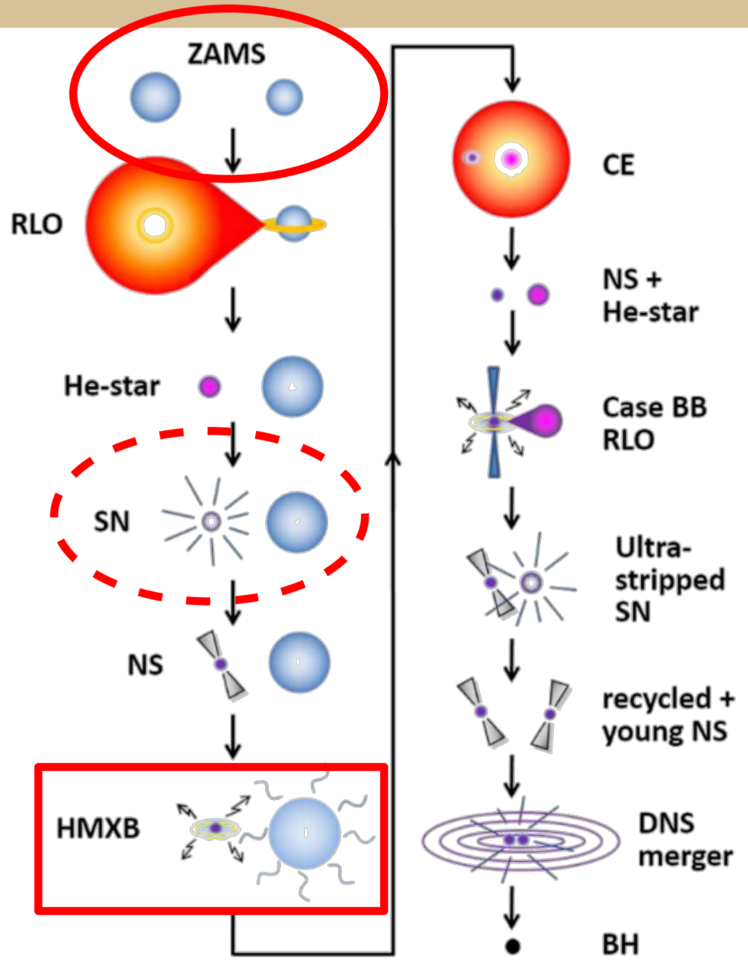
- X-ray systems : just a phase in the life of a binary

Preceded by :

- supernova event
- initial mass transfer

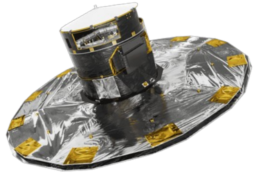
Followed by :

- common envelope
- mass transfer
- another supernova
- final compact merger



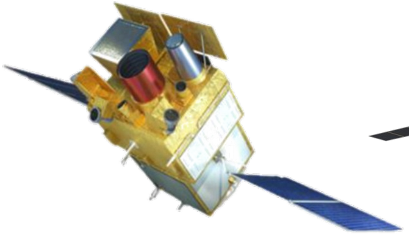
Tauris+2017

Observational prospects

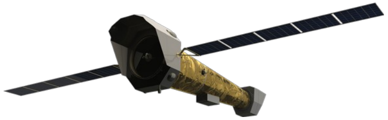


Gaia

LSST

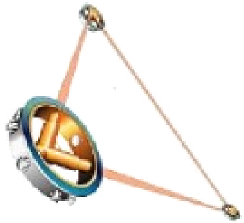


SVOM

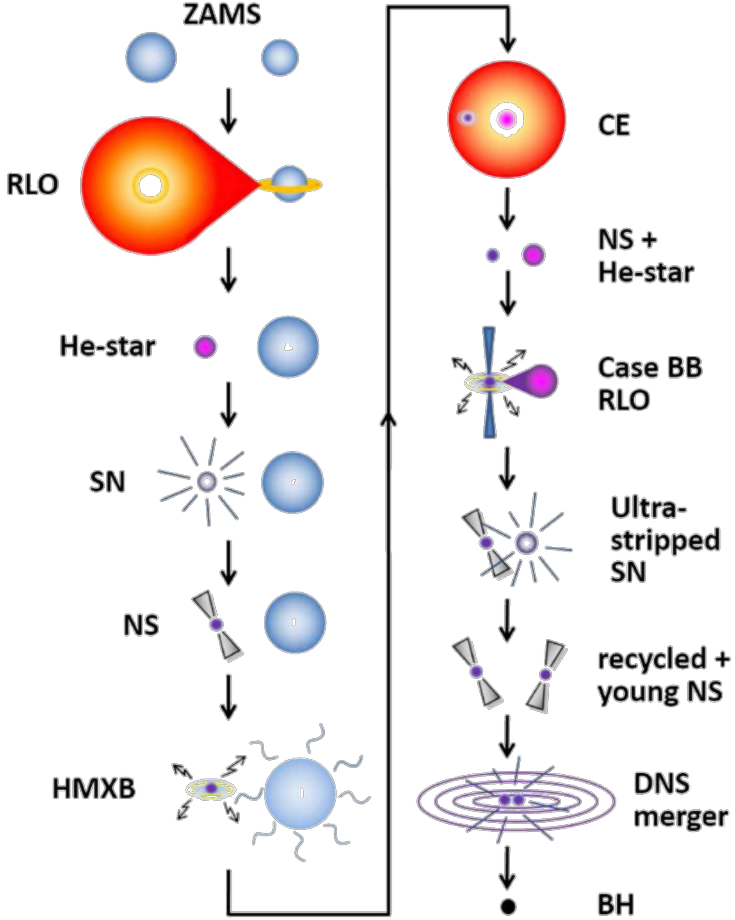


Athena

LIGO / Virgo / KAGRA



LISA



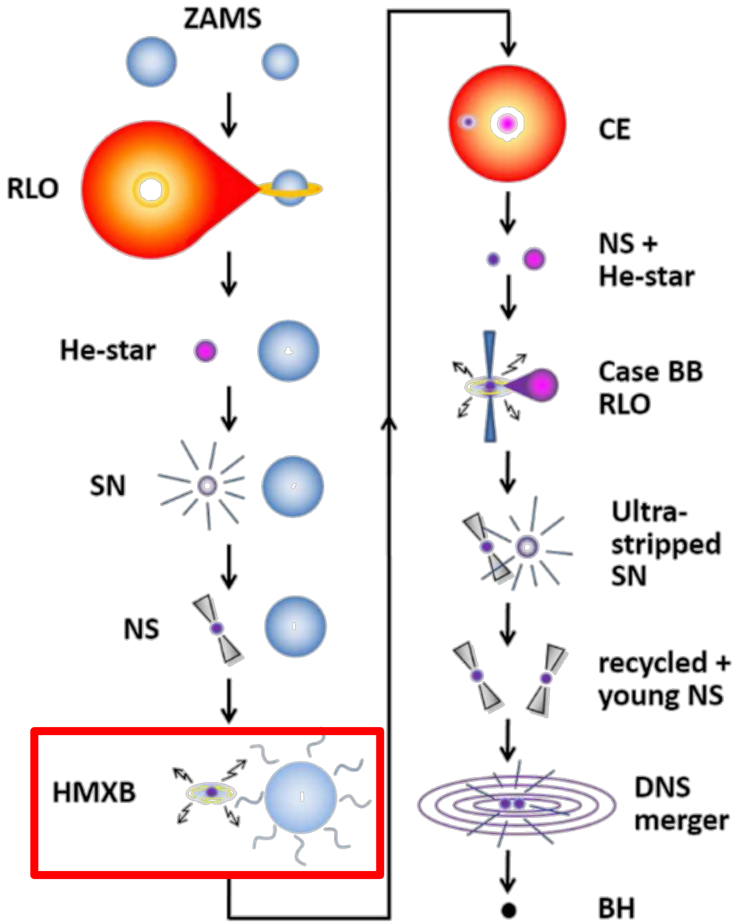
Tauris+2017

Observing the history of binary star systems

I – A catalogue of HMXBs in the Galaxy

II – Impact of the natal kick in binaries

III – Finding the birthplace of stellar systems



X-ray binaries: observational challenges

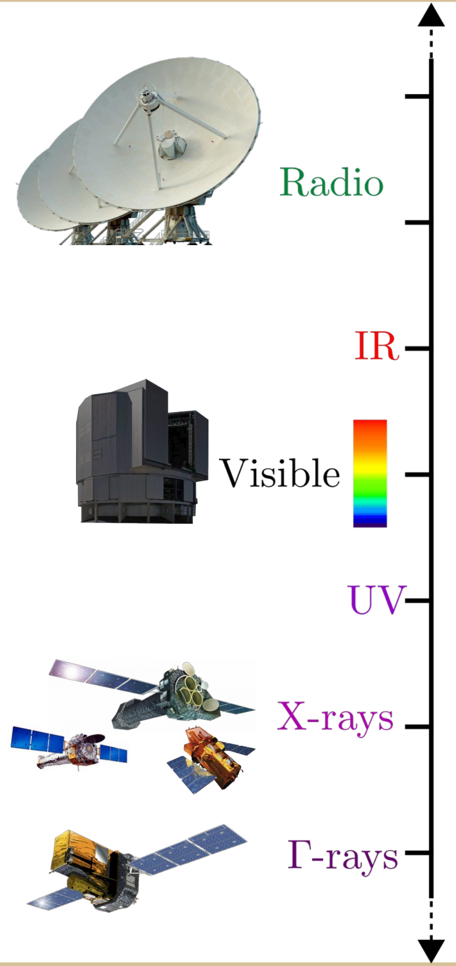
1) discovery in hard X-rays

2) better localization in soft X-rays

3) precise counterpart in optical/nIR

- spectral type of the companion star ?
- (super)orbital period ?
- spin period ?
- radial velocity follow-up ?
- variability ?

→ **Many years & observations are necessary to constrain XRBs**

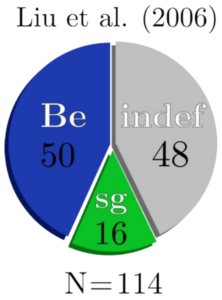


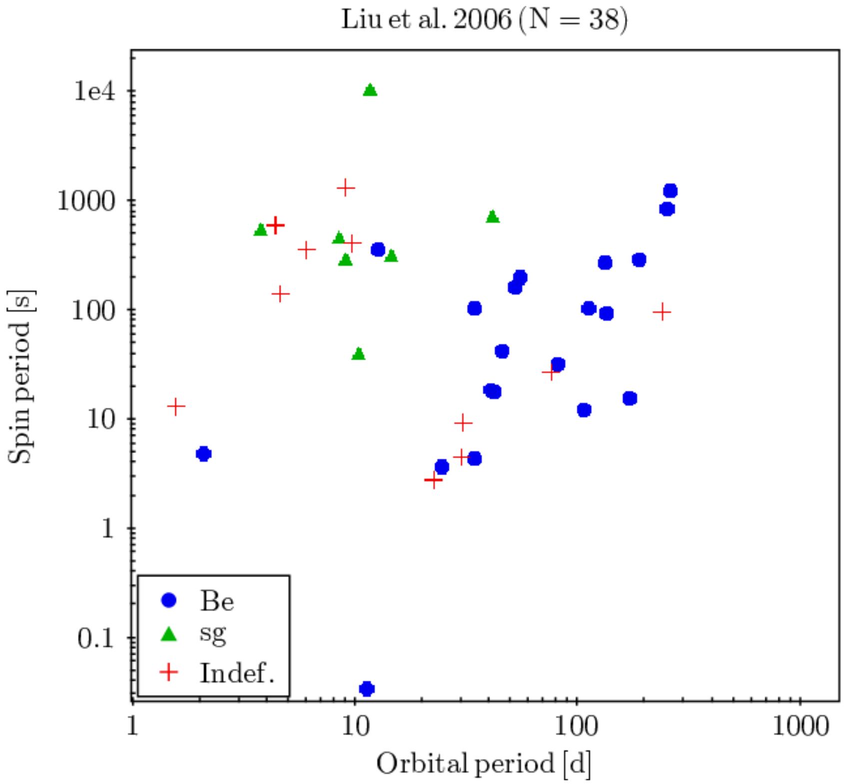
The new catalogue of HMXBs in the Galaxy

Last catalogue of HMXBs : Liu et al. 2006 [114]

→ many new observations since then

→ INTEGRAL was just beginning !





The new catalogue of HMXBs in the Galaxy

Last catalogue of HMXBs : Liu et al. 2006 [114]

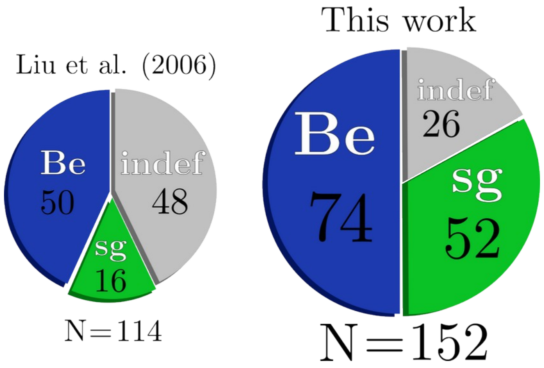
→ many new observations since then

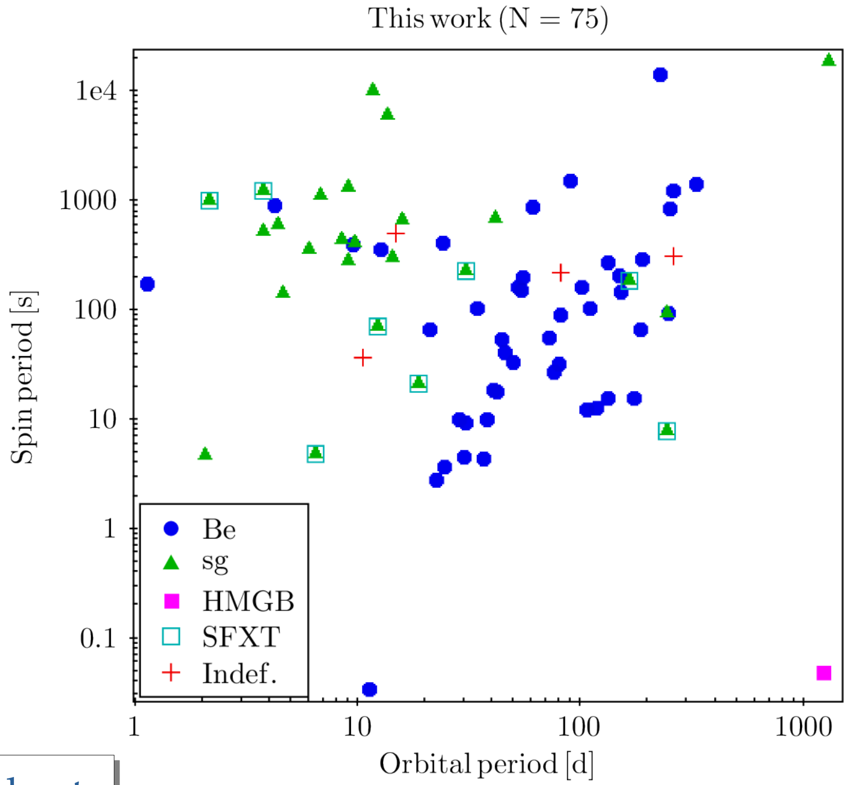
→ INTEGRAL was just beginning !

New catalogue of HMXBs : Fortin et al. 2023 [153]

→ automated search for multi-wavelength counterparts

→ manual search for spectral types, orbital parameters...

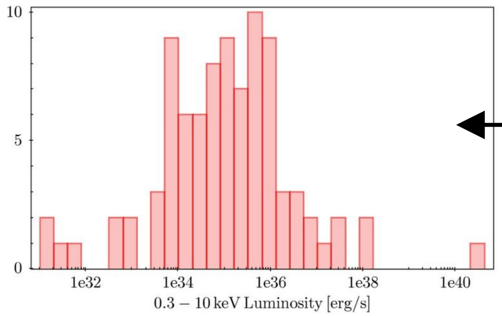


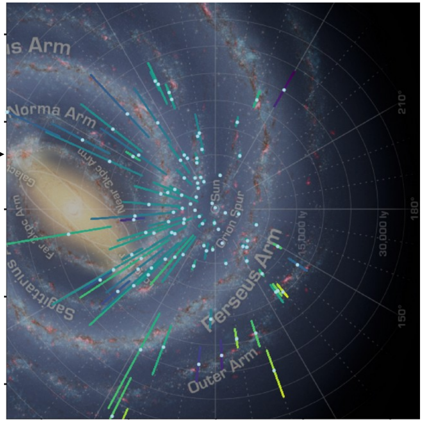


→ GitHub/HMXBwebcat

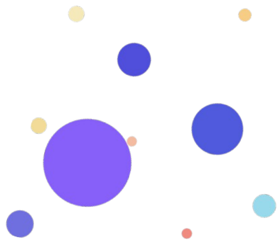
What’s the use ?

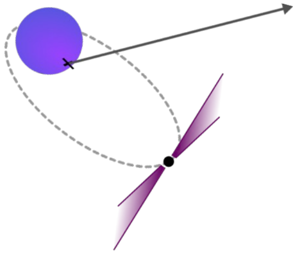
Contribution to X-ray luminosity



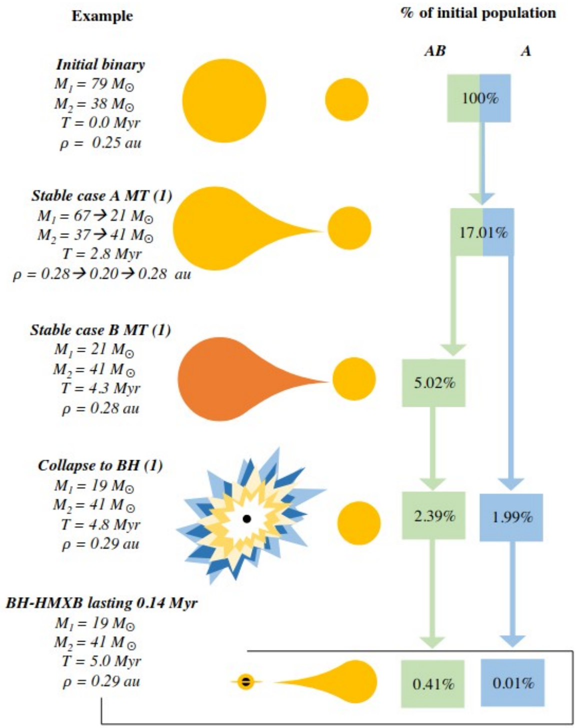


Evolution mechanisms





Population synthesis & compact binaries



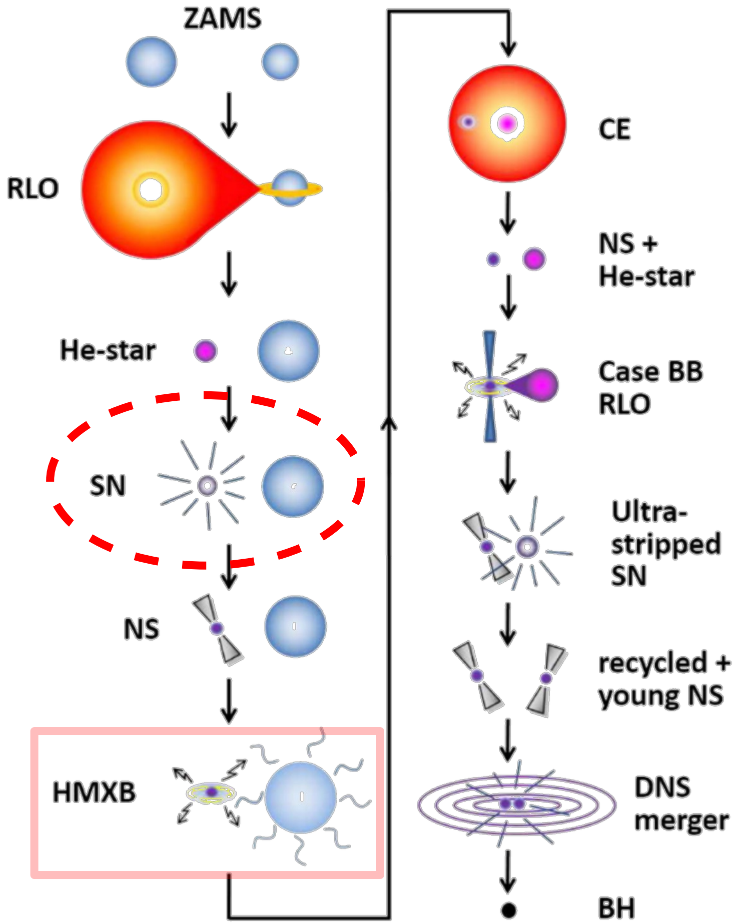
Romero-Shaw+2023

Observing the history of binary star systems

I – A catalogue of HMXBs in the Galaxy

II – Impact of the natal kick in binaries

III – Finding the birthplace of stellar systems



Evolution of High-Mass X-ray Binaries

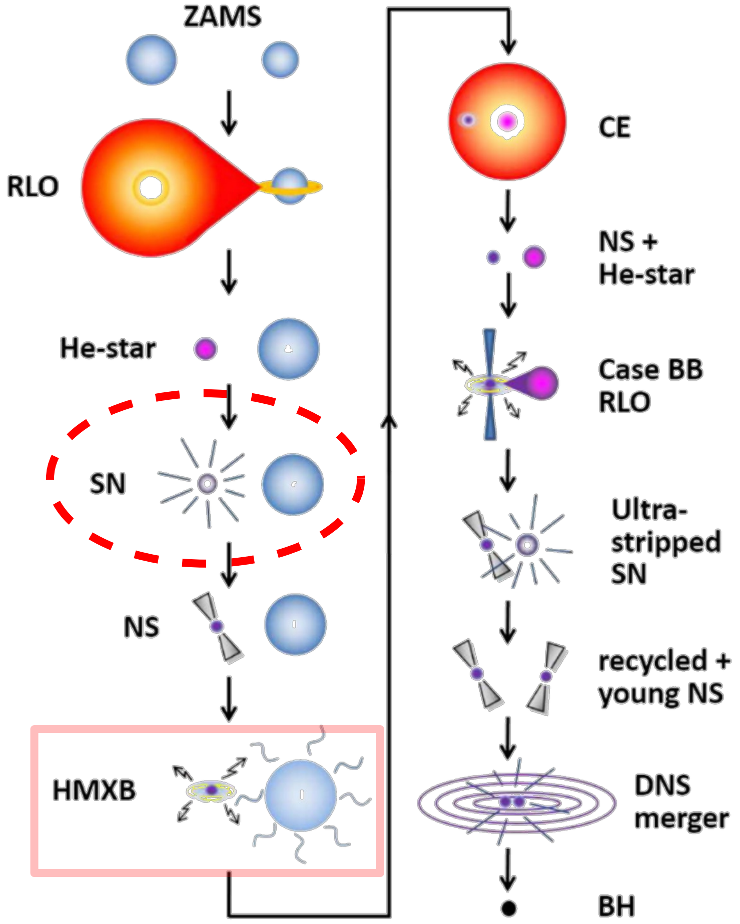
Supernova event associated with the formation of the compact object

→ explosion = mass loss + asymmetry

Orbital parameters govern how binaries will evolve

Survival rate ?

Impact on orbit ?



Tauris+2017

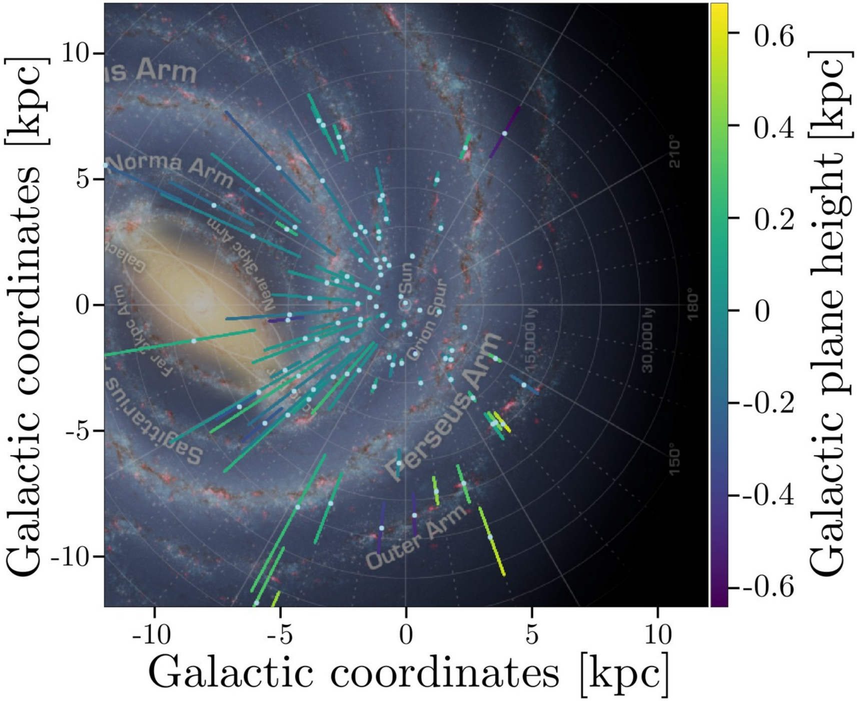
Pre-requisites

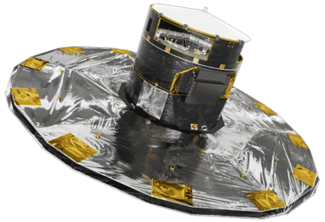
i) Have a catalogue of HMXBs (done !)

ii) Compute their peculiar velocity

→ 6D data (position + proper motion + radial velocity)

Peculiar Velocity = Velocity – Galactic orbital motion





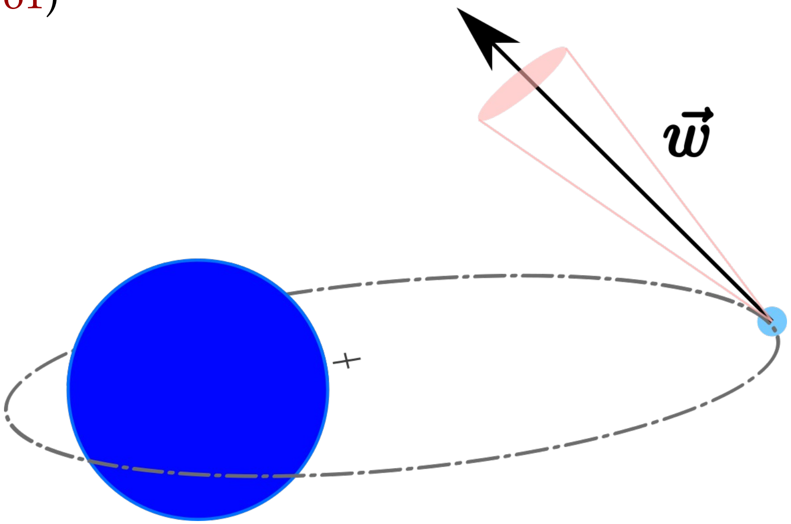
Gaia: astrometric optical survey

→ sky position + distance + proper motion

Deriving neutron star kicks

Analytical equation linking pre-SN to post-SN orbital parameters (Kalogera 1996), assuming an **isotropic probability of the kick direction**.

- Blaauw kick (spherically symmetric mass loss, Blaauw 1961)
- Asymmetric kick (random direction)



Hypotheses:

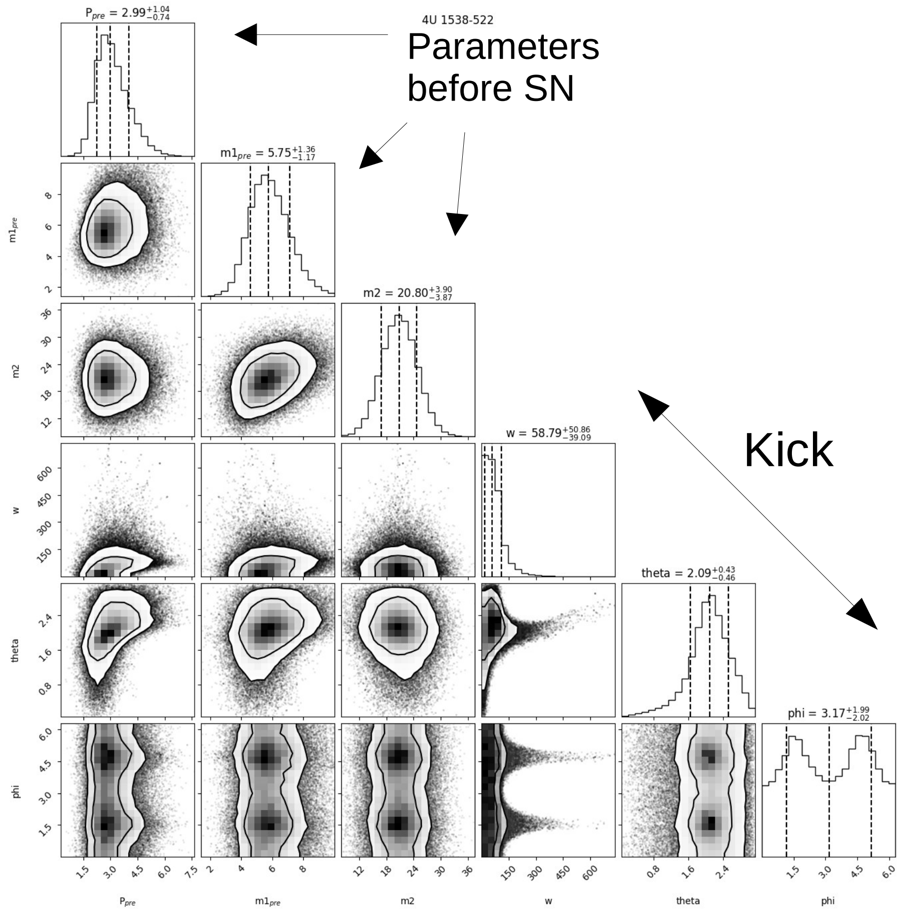
- circularized systems Dosopoulou & Kalogera 2016
- fixed NS mass @ $1.4M_{Sun}$ Kiziltan+2013
- companion is unaffected by the supernova Liu+2015

Deriving neutron star kicks

Bayesian approach:

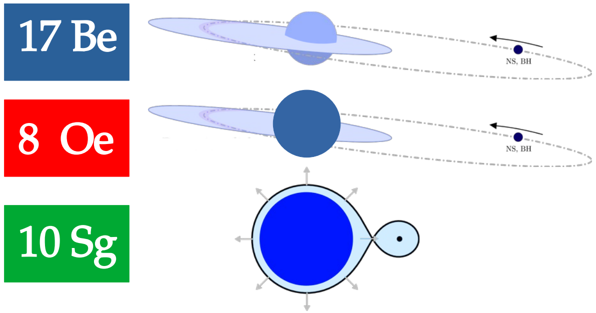
- Priors on kick magnitude, initial P_{orb} and pre-SN mass
- Likelyhoods: Gaia observables, companion mass, P_{orb} & eccentricity

→ Explore the posterior distributions using Markov Chain Monte Carlo (MCMC)



Results on kick distributions

Inferred kick magnitudes on 35 HMXB :

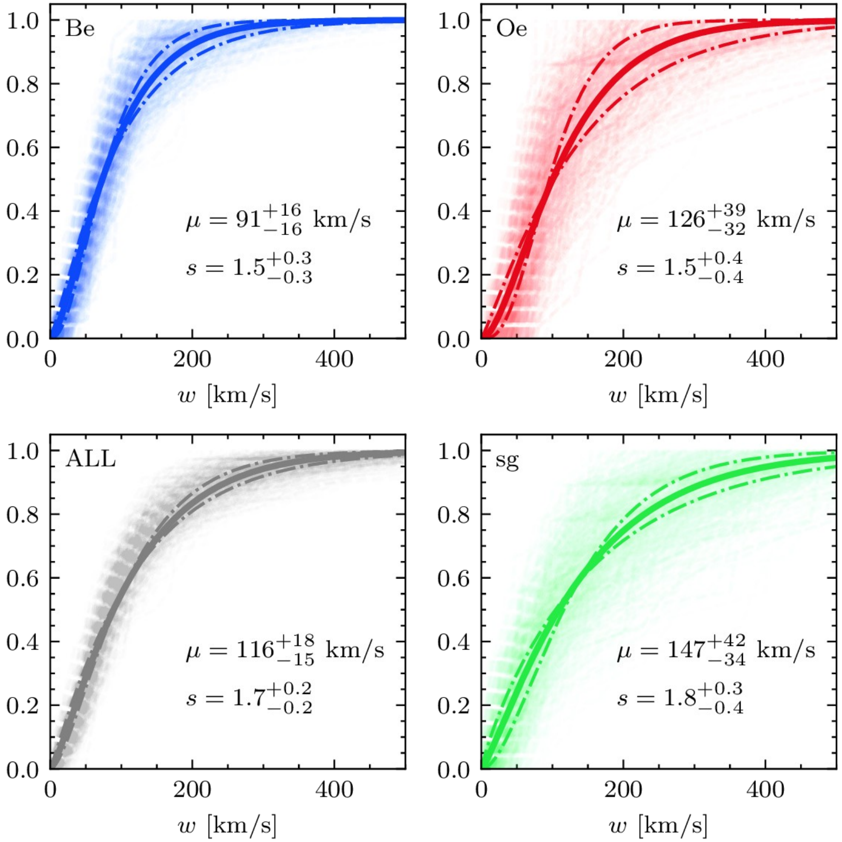


Kick magnitude + pre-SN mass + disrupted fraction

Low natal kicks: stripped SN events

→ useful for population synthesis models ?

Cumulative distributions of kicks

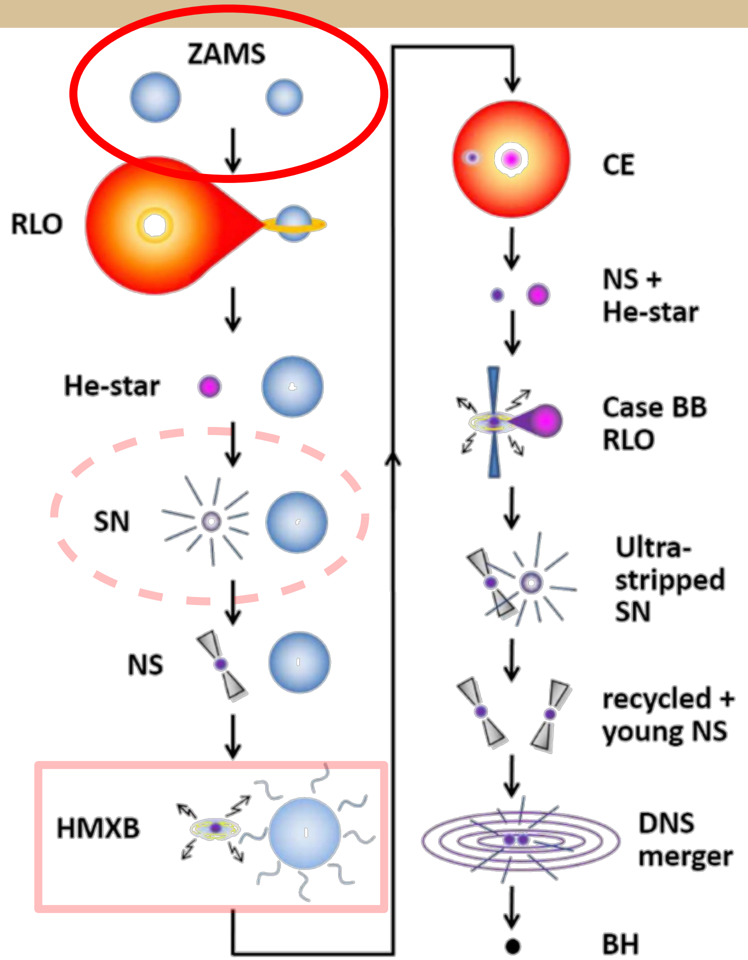


Observing the history of binary star systems

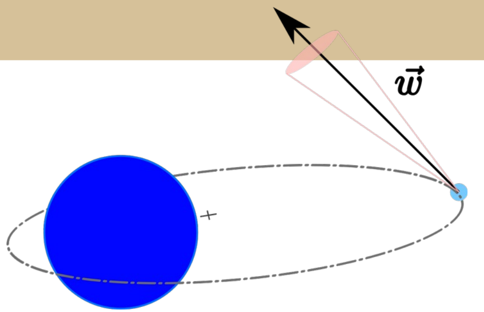
I – A catalogue of HMXBs in the Galaxy

II – Impact of the natal kick in binaries

III – Finding the birthplace of stellar systems



Natal kick & migration from birth site



Supernova event = neutron star (or black hole) **natal kick.**

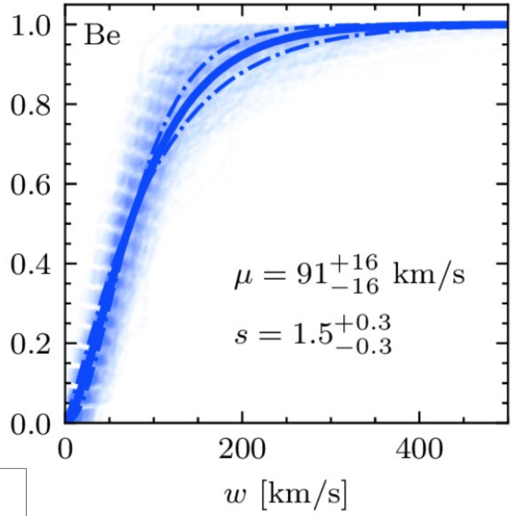
→ impact on orbital parameters (P_{orb}, eccentricity)

→ survivability (large kick → unbound system ?)

→ imprint on the peculiar velocity of the whole system

Order of magnitude : Vpec ~100 km/s → migration of ~ 100 pc/Myr

Even if HMXBs are young (few dozen Myr), migration distance can be high.



Fortin et al. 2022b

Birthplace of HMXBs and Galactic ecology

- Galactic structures susceptible of hosting massive star formation :

  young open clusters, spiral arms, isolated ?

Question

How do HMXBs fit in the Galactic ecology ?

What we get

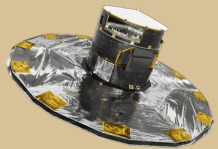
Infer the age of HMXBs since the first supernova event

→ evolution timescales, formation scenarios, history…

Correlation between spiral arms and/or OB associations in Milky Way : Bodaghee+2012, Coleiro+2013

→ **Need accurate kinematical data !**

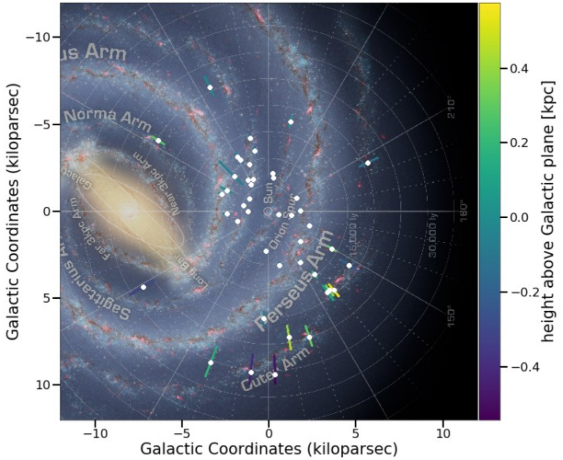
Astrometry from Gaia EDR3



High-Mass X-ray Binaries

Fortin+2022b

- 94 confirmed in Milky Way
- 80 observed by Gaia
- **26 with full 6-D astrometry**

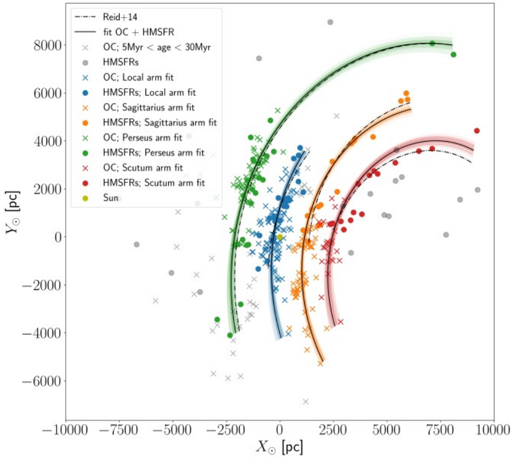


Galactic spiral arms

Castro-Ginard+2021

- Local, Sagittarius, Perseus, Scutum
- shape + motion

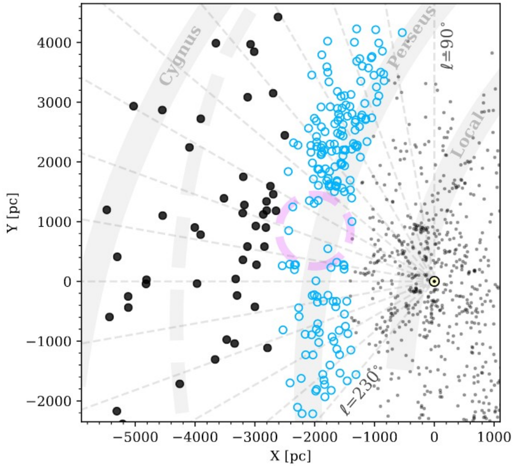
$$\ln \frac{R_G}{R_{G,ref}} = -(\theta_G - \theta_{G,ref}) \tan \psi$$



Open stellar clusters

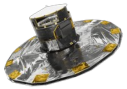
Cantat-Gaudin+2020

- 2017 within ~5kpc
- age from HR isochrone fitting
- **1381 with full 6-D astrometry**



Integration of orbit around the Milky Way

- Use of python module *Galpy* to initialize & integrate the motion of HMXBs and clusters
- MWPotential2014 (Bovy 2015) : bulge + disk + dark matter halo
- 500 timesteps of 0.2 Myr → explore the orbits until 100 Myr ago



Gaia astrometry is very accurate ! ... but not perfect :(

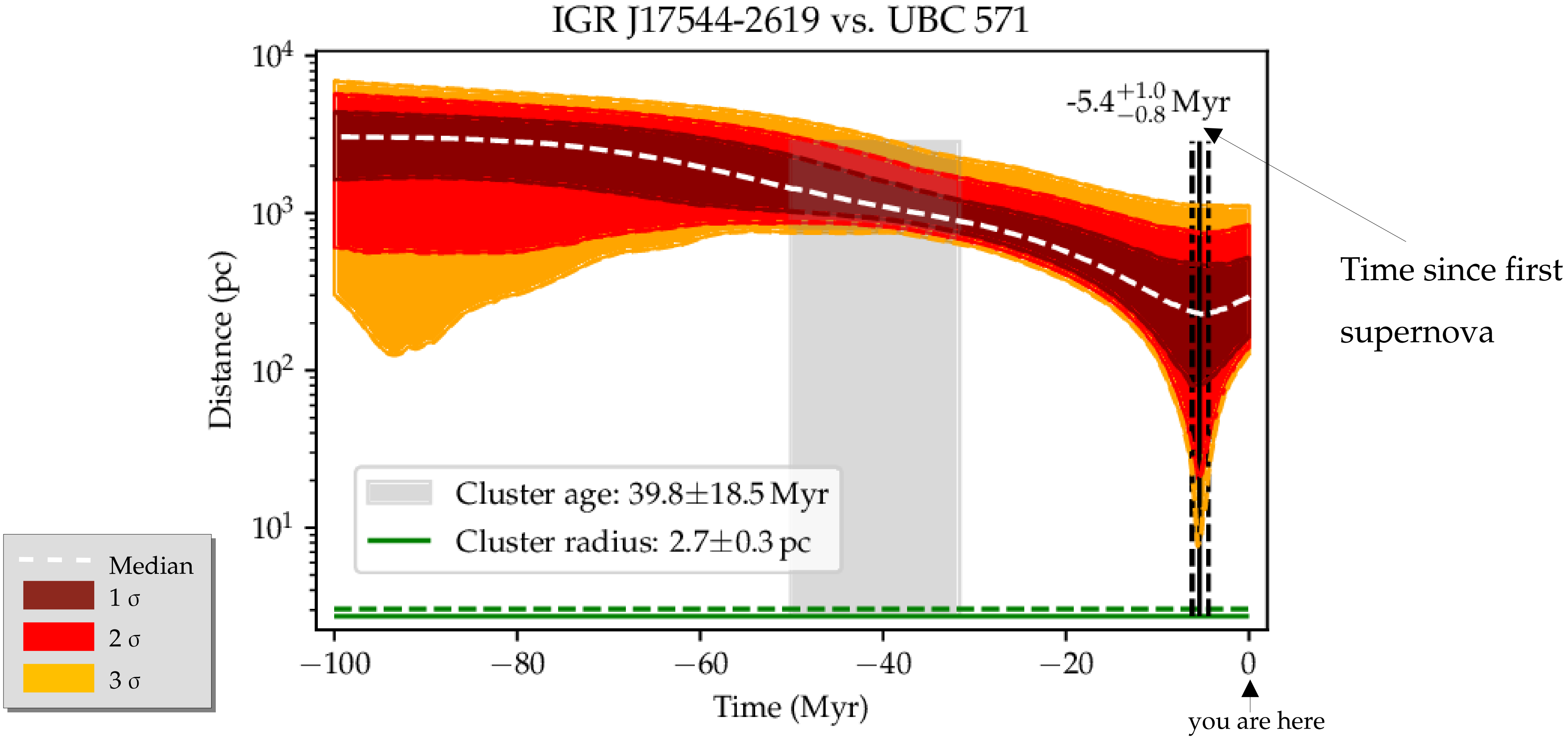
→ 1000 orbit integrations using initial parameters drawn from distributions according to Gaia data

- We obtain, for each timestep, a distribution of possible positions & velocities

→ Compute the possible distances to clusters and spiral arms to find **encounter candidates.**

→ simple galactic potential, low sample size → not too CPU-intensive

Encounter detection: time-distance histograms



General results – Birthplace statistics

Open Cluster	tSN [Myr]
1A 0114+650	4.4
LS I+61 303	15
X Per	24
HD 259440	38
4U 1700-377	1.9
IGR J17544-2619	5.4
Cyg X-1	4.4

7

Spiral arm	tSN [Myr]
1A 0535+262	18
2FGL J1019.0-5856	10
Cen X-3	1.9
1E 1145.1-6141	25
4U 1538-522	10
IGR J18450-0435	20
SS 433	<60
4U 2206+543	25

8

Isolated ?

IGR J00370+6122
IGR J08408-4503
Vela X-1
GX 301-2
PSR B1259-63
LS 5039
MWC 656

7

Happy birthday !

:(

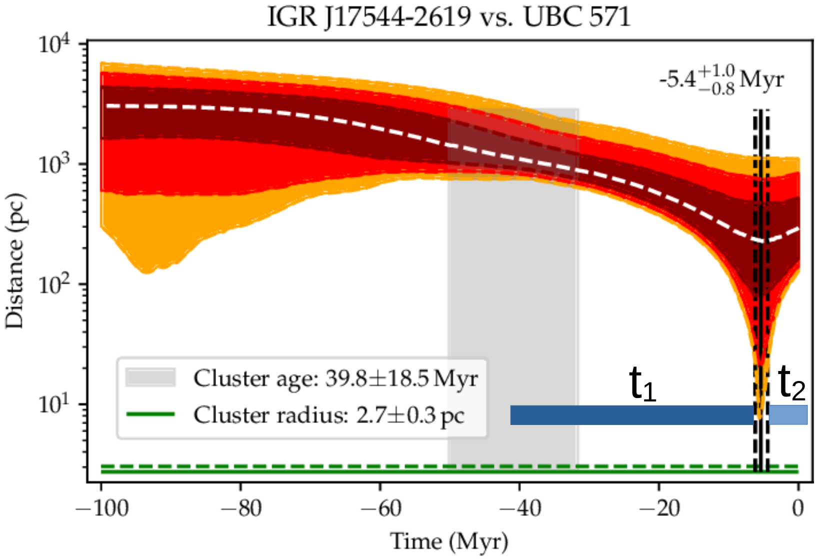
- HMXBs can have encounters with both clusters and spiral arms

→ degeneracy is always lifted when taking into account companion mass & evolution timescales

Actual results : ZAMS masses, and more

Mass – Age relation for massive stars (10 – 60 M⊙) : $\frac{M}{M_\odot} = \left[10^{-4}\left(\frac{t_{ZAMS}}{Myr}\right)\right]^{\frac{1}{1-\alpha}}$; $\alpha = 3.125$ (Figueiredo+1991)

Cluster encounters give primary star lifetime (**t_1**) and age since supernova (**t_2**) :



$t_1 \rightarrow M_{1,i} = 14.4$ +/- $0.2\ M_\odot$		Primary ZAMS mass
$t_1 + t_2 \rightarrow M_{2,i} \leqslant 13.5$ +/- $1.8\ M_\odot$		Secondary ZAMS mass (upper limit)
$M_{2,f} = 23\ M_\odot \rightarrow M_{acc} \geqslant 9.5\ M_\odot$		Initial mass transfer (lower limit)
$M_{1,\ pre\text{-}SN} \leqslant 4.9\ M_\odot$		Pre-supernova mass (upper limit)

→ Binary evolution through kinematics

Conclusion & Prospects

- X-ray binaries are challenging to observe

 → the latest catalogue updates the INTEGRAL – Gaia era

- We can observe their past using current optical/IR facilities

 → constraining impact of first supernova

 → date & place of birth : binary evolution history

- Next generation of observatories coming right now !

 LSST, SVOM, eRosita (?), and Athena later on

- Gravitational waves: probing the future of X-ray binaries

 LIGO/Virgo/KAGRA O4 coming on May 24th for 18 months,

 hopefully lots of neutron star merger events like 17/08/2017

Attendance reward:

European Robin, Angers, FR

Extra: Disrupted systems, isolated NS velocities

Tauris & Takens 1998 : equations for velocity of a NS kicked-out of the binary after the SN event

Observed velocity distribution of isolated radio pulsars :

Hobbs+2005 → **265 km/s**

Igoshev 2020 → **230 km/s** (or 146 + 317 km/s)

We keep track of disrupted systems (5 to 50% of simulation outcomes depending on the binary)

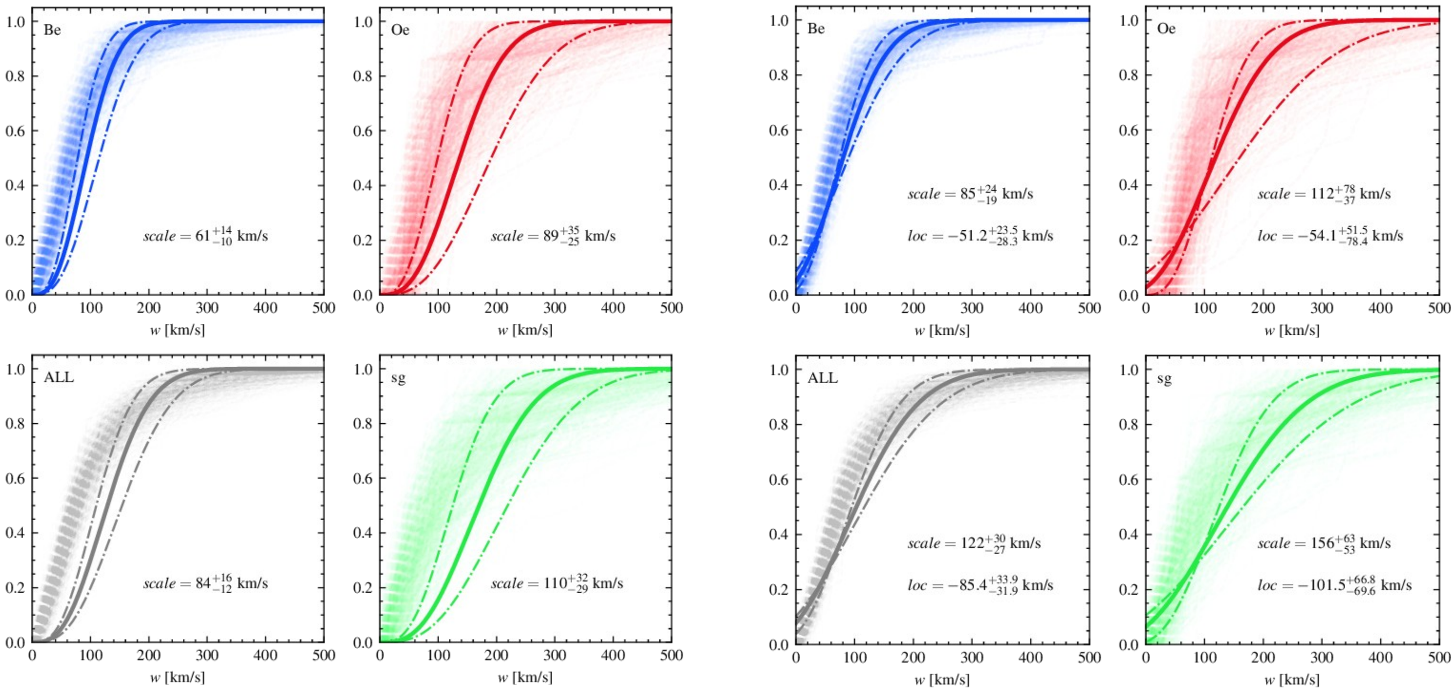
→ NS velocity from disrupted systems in our sample : **110 km/s**

→ In case of disruption, < 3% result in fast pulsars (> 500 km/s, large initial period > 1000 d required)

→ Binary evolution unlikely to be a formation channel for fast isolated NS.

Extra: Maxwellian vs. Gamma

Maxwellian is historically used to model kicks in isolated pulsars (Hobbs+2005, Ng & Romani 2007, Noutsos+2013)



Classical Maxwellian

Shifted Maxwellian

Unbound systems ?

→ observed vs. pop synth.

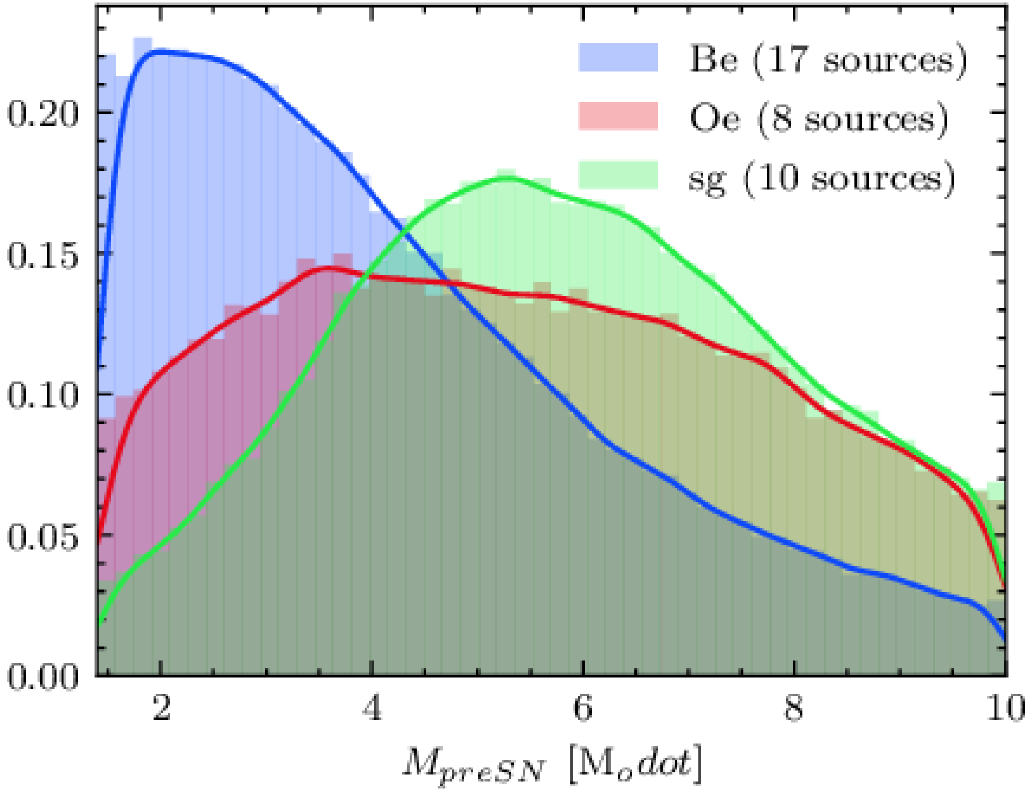
Stripped progenitors ?

→ lower pre-SN mass

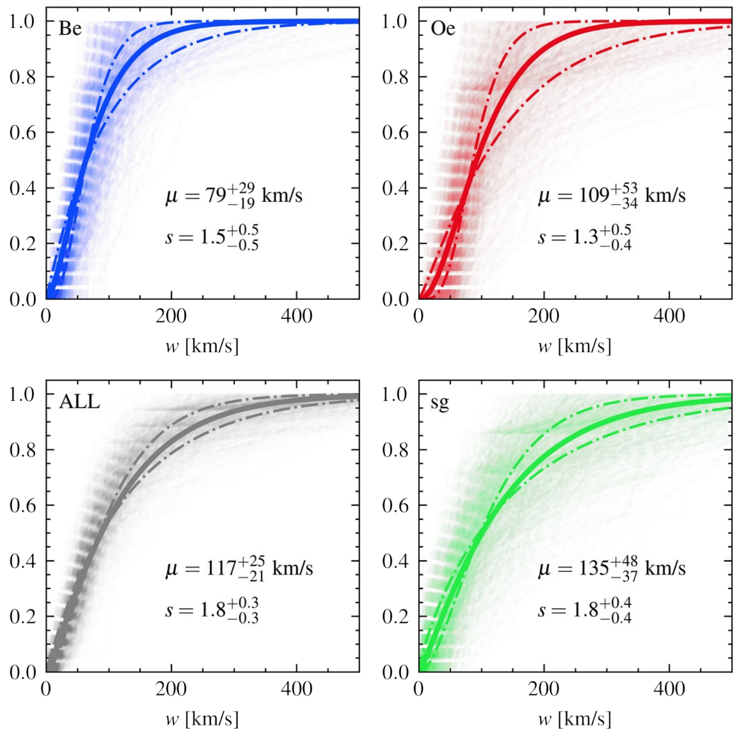
Kick isotropy ?

→ NS spin axis

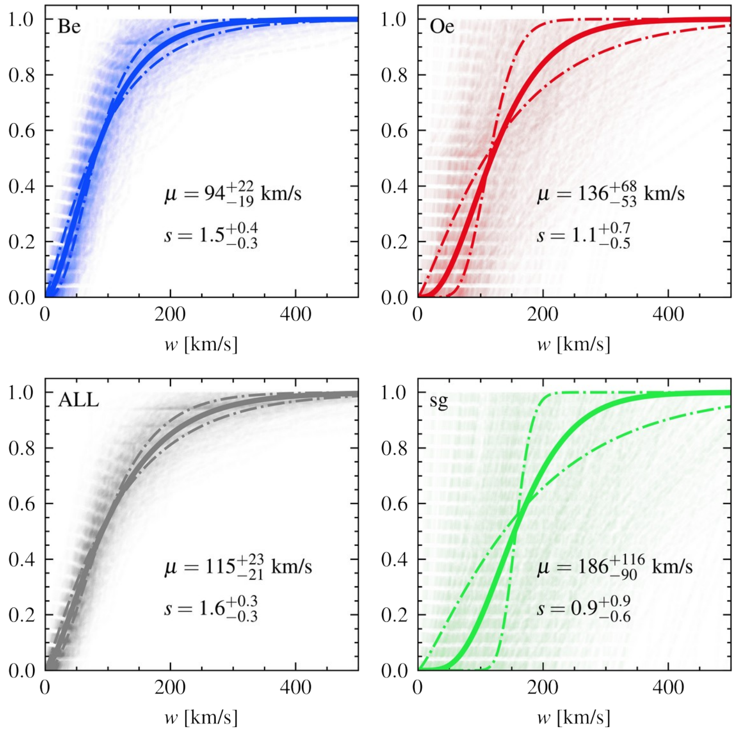
Extra: $M_{\text{pre-SN}}$ distribution



Extra: impact of missing radial velocity



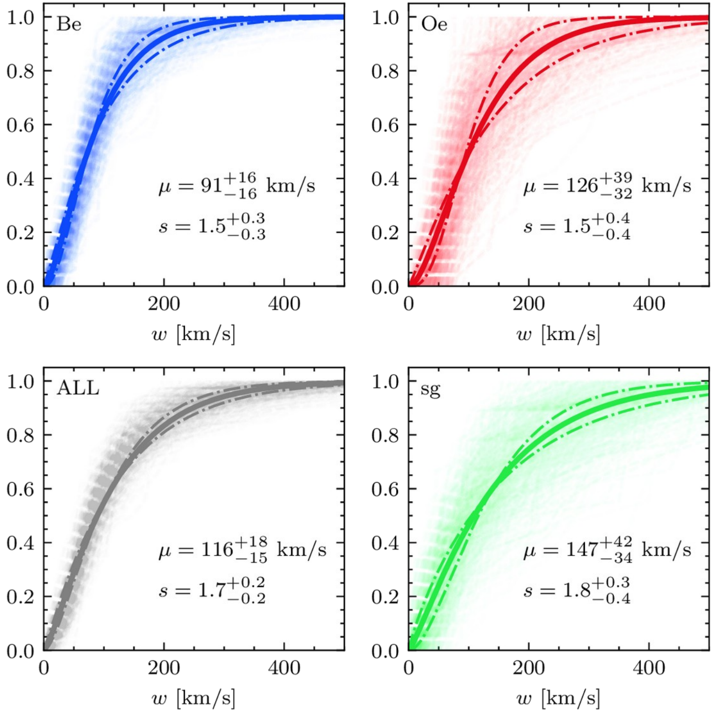
With RV only



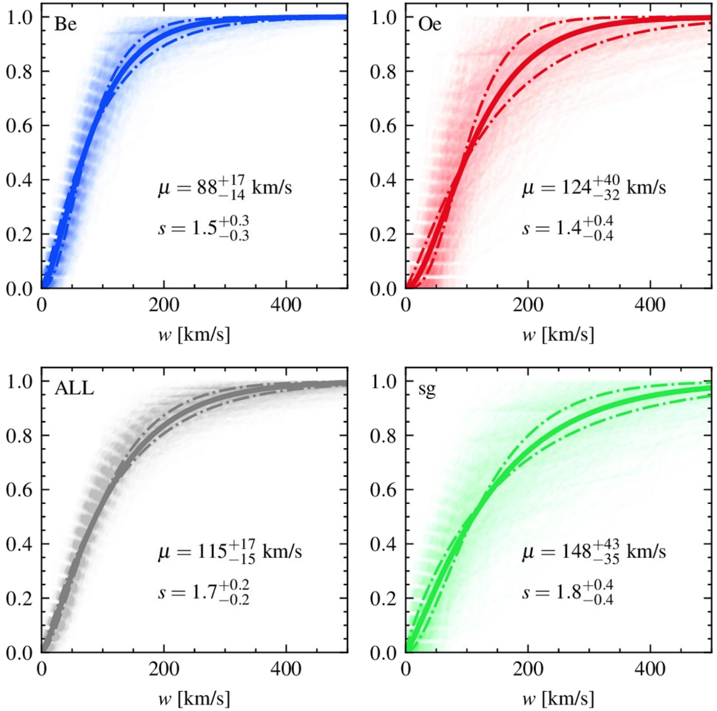
Without RV only

Extra: impact of neutron star mass

→ Assumed constant NS mass of 1.4 Msun, what about more massive NSs ?



$M_{NS} = 1.4\ M_{Sun}$



$M_{NS} = 1.8\ M_{Sun}$

No notable difference on the fitted parameters

→ NS mass variation are much smaller than $M_{pre\text{-}SN}$ uncertainty

Extra: building the list of HMXBs

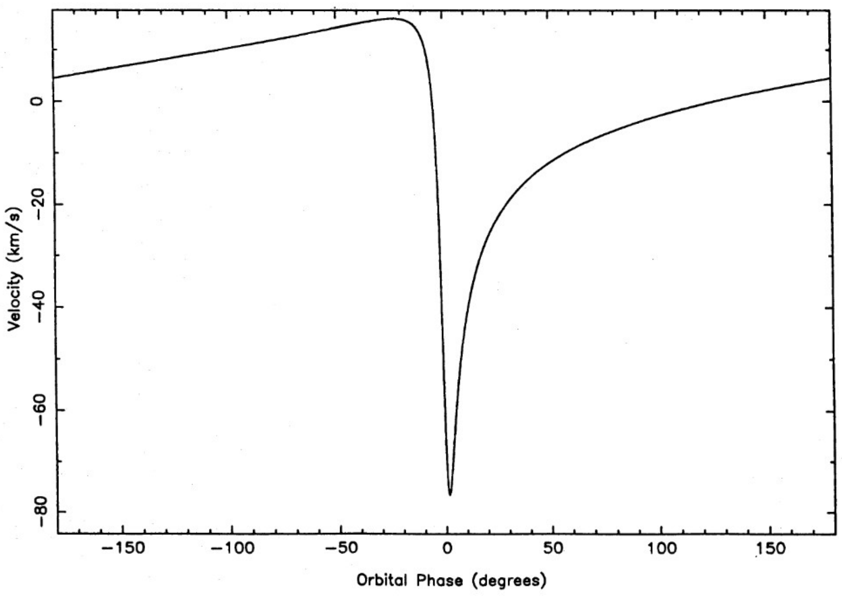
Example: PSR B1259-63

Radial velocity followup of the Oe companion star

→ Curve is presented but no value of the systemic velocity is given in the paper !

→ WebPlotDigitizer: we retrieved the data from the plot and fitted the systemic velocity

→ Do that for 130 HMXBs in the Galaxy.



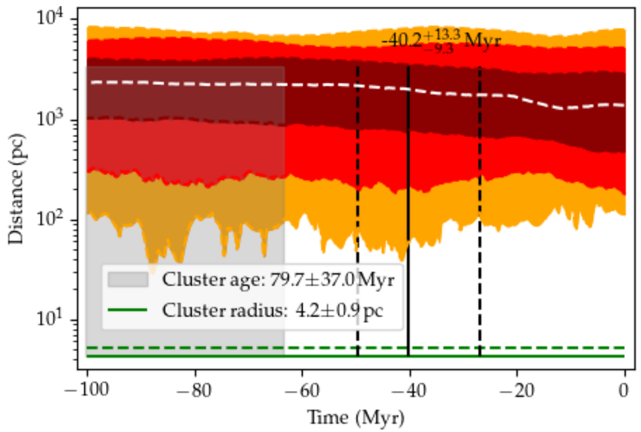
Radial velocity of PSR B1259-63 (Johnston+1994)

Encounter detection : validity of the method

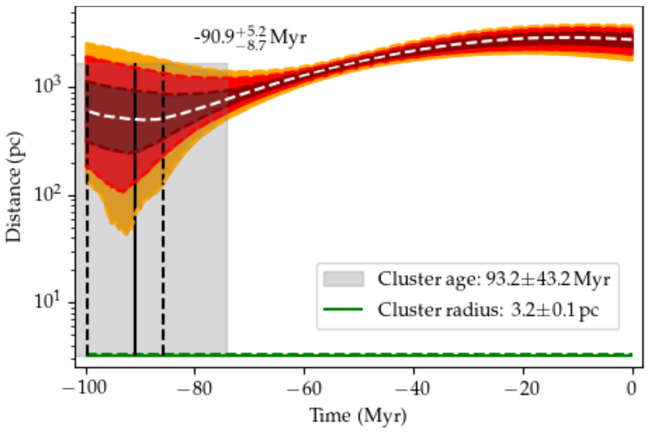
→ Simulations over randomly generated HMXBs and clusters to test the ability to find a birthplace

- chose a random birth date in [1 : 100] Myr
- initialize a birth cluster at a random position + velocity
- initialize HMXB born somewhere near the cluster
- apply random natal kick to HMXB
- integrate both orbits up until today
- generate dummy Gaia astrometry for HMXB & cluster of random quality (according to real data)
- look for an encounter

Encounter detection : validity of the method

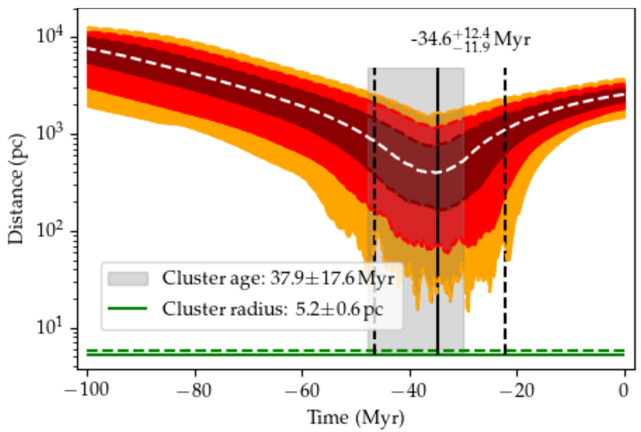


← Bad astrometry : 10% failed cases



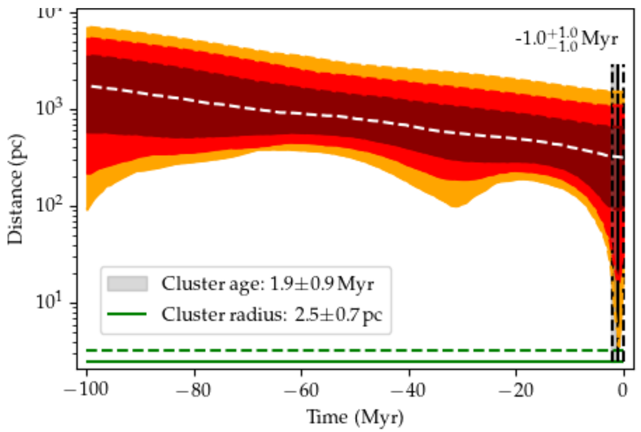
Good astrometry →

retrieve old encounters



produce both sharp →

← and wide distributions



- Gaia parallax → distances ≲ 5kpc

→ drastic decrease in known clusters with distance